International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 3 Issue 6 ǁ June 2015 ǁ PP.25-28

Resonant-tunneling-diode effect in Si-based double-barrier structure sputtered at room temperature

Yuang-Tung Cheng[1], Jyh-Jier Ho[1*], Tang-Yu Wei[1], Jia-Show Ho[2], Sheng-Shih Wang[1], Jie-Xian Lin[1], Chi-Hsiao Yeh[3] and Kang L. Wang[2]

[1]Dept. of Electrical Engineering, National Taiwan Ocean University, No. 2 Pei-ning Rd., Keelung 20224, Taiwan.

[2]Dept. of Electrical Engineering, U. of California, Los Angeles, CA 90095, U.S.A.

[3]Dept. of Surgery, Chang Gung Memorial Hospital, Keelung 20400, Taiwan.

Abstract: This paper presents the resonant-tunneling-diode (RTD) effect in a SiO_2/n-Si/SiO_2/p-Si double-barrier structural thin films fabricated using radio frequency (RF) magnetron sputtering at room temperature (300 K). The implementation of a circuit prototype is first accomplished by modulating a Si-based RTD with a solar-cell bias voltage. The important electrical properties of the peak current density and peak-to-valley current ratio (PVCR) are 184 nA/cm^2 and 1.67, respectively. The connection between the two RTDs in series is biased by a solar cell. The value of the switching transition time is 24.37 μs; oscillation occurs with an operating frequency of 41.6 KHz. In semiconductor applications, the developed RTD is characterized by stability, enduring environmentally elevated temperature and relative humidity.

Keyword: Resonant-tunneling-diode (RTD), Structural, Thin films, Peak-to-valley current ratio (PVCR), Semiconductor.

I. Introduction

It is known that resonant tunneling diodes (RTDs) fabricated with a semiconductor double-barrier structure possess desirable physical and functional features. In particular, RTDs that exhibit negative differential resistance (NDR) in their current–voltage (I–V) characteristics are very useful in circuit applications such as microwave oscillators, switching devices, and frequency dividers [1, 2]. However, most of these RTDs utilize III–V semiconductor materials, which are expensive and incompatible with mainstream Si-based integrated-circuit technology. By fully taking advantage of Si-based NDR devices, we can reduce the circuit complexity to enhance circuit performance in terms of chip area and power consumption [3]. In this letter, we present a novel implementation with a monostable–bistable transition logic element (MOBILE) circuit consisting of two RTDs connected in series [4]. In this device, the input terminal is driven by a solar-cell biasing voltage. The implementation of this concept on a Si substrate is useful for further improvement of digital circuits driven by solar cells [5].

II. Experiment

The device structure employed in this study is shown in the lower-left inset of Fig. 1. The lower barrier layer (of SiO_2) is first directly deposited by radio frequency (RF) magnetron sputtering on an (100)-oriented *n*-type Si substrate at room temperature (300 K). After a layer of p-Si (1.5 μm) is deposited, a quantum well is obtained using a layer-by-layer deposition technique. A second SiO_2 layer is deposited by RF magnetron sputtering under similar conditions as those of the lower barrier layer. A set of low-J_p (J_p is the peak current) RTDs with a SiO_2 barrier thickness of from 0.6 to 1.8 μm are fabricated so that the device with the lowest value of J_p may be selected for use in digital circuit applications. The final Al electrodes on the top and base substrate (with an area of 177 × 177 μm^2) are deposited by evaporation using the photoresist mask method.

The thin-film thickness is measured by a New Span Opto-technology Inc. microscope (model: TF-166). To observe the NDR of the Si/SiO_2 system, I–V measurements are performed using a Keithley instrument (model 2420). An Instek GDS820S oscilloscope is used to measure the high-speed oscillator in the RTDs-MOBILE circuit.

III. Results and Discussion

The use of a Si-based RTD with NDR characteristics at low voltages can reduce power consumption. This letter shows an implementation of a voltage-controlled oscillator (VCO) with extremely low power consumption based on the SiO_2/p-Si/SiO_2/n-Si structure. The formation of the double-barrier SiO_2 layers and the single p-Si layer is crucial for developing these single-electron devices. The basic device mechanism is shown in the upper-right inset of Fig. 1. By sandwiching a narrow band-gap material (p-Si) between two large band-gap materials (SiO_2), a quantum well is formed. At zero bias voltage there are no available states in the well; therefore, there is no current flow. When a critical value of the forward bias voltage is applied, the energy levels inside the well are lowered in such a way that resonance occurs. Fig. 1 shows the room-temperature I–V characteristics of the fabricated RTD structures with different barrier thicknesses and a 1.5-μm-thick quantum well. The fabricated 0.6-μm-barrier RTD forms a VCO with a power consumption of 258 nW/cm^2 with J_P = 184 nA/cm^2 and a peak voltage (V_P) of 1.4 V. When the SiO_2 thickness is 1.2 μm, J_P and V_P are 198 nA/cm^2 and 2.4 V, respectively; the corresponding DC power of the VCO is 474 nW/cm^2. In contrast, the barrier sample 1.8 μm in thickness produces values of J_P, V_P, and VOC of 280 nA/cm^2, 5.8 V, and 1.6 μW/cm^2, respectively. Measurement of the distributions of V_p and J_p shows that the V_p and J_p deviations become larger when the barriers become thicker. Therefore, we can conclude that the values of V_p and J_p of the RTD depend on the barrier thickness.

The purpose of this letter is to propose a novel Si-based RTD oscillation circuit and to estimate its performance. The large-signal phenomenon in the RTD, *i.e*., switching from the peak state to the valley state in the I–V characteristics, is applied in the designed circuit. The circuit model of the MOBILE circuit is shown in the right inset of Fig. 2. The MOBILE device consists of two serially connected RTD devices (load RTD_1 and driver RTD_2) and is driven by an oscillating bias voltage. When oscillation occurs because of the applied solar-cell bias voltage, the circuit acts as a logic gate. The expected switching time can be calculated [6] or measured using electro-optical sampling techniques [7]. The switching speed (or rise time) of the RTD is directly proportional to the ratio of the peak current to the capacitance. To determine the switching speed, the load lines of the RTD are constructed, and the voltages are extracted, as shown in Fig. 2. The experimental capacitance of 1.64 pF is used to determine the switching speed. The obtained values of the power and V_p are 258 nW/cm^2 and 1.4 V, respectively. The RTD results exhibit a PVCR of 1.67 at room temperature at J_P = 184 nA/cm^2. The value of the switching time is obtained as 24.37 μs, showing the proposed circuit's potential for high-speed applications. From the results of the above investigation, high-speed operation of the proposed device is also expected. An oscilloscope capture of the measured waveforms from the word line and the bit line are shown in Fig. 2 in the upper-left inset. Switching is demonstrated for different solar-cell bias voltages. As the RTD switches, a step waveform begins to propagate along the transmission line. The result shows oscillation at an operating frequency of 41.6 KHz. The decrease in the tunneling current density with an increase in the bias voltage affects the I–V characteristics of the NDR.

Although the three parameters, V_T (threshold voltages), R_T (junction resistance), and C_P (parasitic capacitance), may vary with temperature, our results show that the RTDs remain stable over time, as seen in Fig. 3 on the bottom-left axes. Similarly, the two parameters, V_T and J_S (reverse saturation current), may vary with the relative humidity (RH). This result shows that our RTDs remain stable over time, as is seen in Fig. 3 on the top-right axes. These results clearly demonstrate that our RTDs are stable and are applicable to a wide variety of applications.

IV. Conclusion

SiO_2/n-Si/SiO_2/p-Si RTDs with three different barrier thicknesses are fabricated using traditional RF magnetron sputtering, and the barrier-thickness dependence of J_P is measured. A MOBILE circuit that utilizes a pair of RTDs connected in series and is driven by a solar-cell bias voltage has been demonstrated. The RTDs result in a PVCR of 1.67, J_P = 184 nA/cm^2, and a switching cycle time of 24.37 μs. The investigated Si-based RTD devices are simple, robust, and versatile. The developed results illustrate the high stability of Si-based RTDs for applications such as switching, oscillators, logic circuitry, and frequency dividers.

V. Acknowledgement:

The authors acknowledge the assistance and partial financial support of Ministry of Science and Technology (NSC 102-2221-E-019-040-MY3), and Chang Gung Memorial Hospital (CMRPG 2B0511, CMRPG 2B0521, CMRPG 2B0531, and CMRPG 2B0541) of Taiwan, respectively. Mr. S. Wang especially appreciates the support of China University of Science and Technology (Taiwan).

References

[1] Choi S, Jeong Y, Yang K. Low DC-power Ku-band differential VCO based on an RTD/HBT MMIC Technology. IEEE Microw Wireless Compon Lett. 2005; 15 (11): 742-4.

[2] Worschech L, Hartmann F, Kim TY, Höfling S, Kamp M, Forchel A, et al. Universal and reconfigurable logic gates in a compact three-terminal resonant tunneling diode. Appl Phys Lett. 2010; 96 042112: 1-3.

[3] Asaoka N, Funato H, Suhara M, Okumura T. Fabrication and characterization of GaInP/GaAs triple barrier resonant tunneling diodes grown by MOCVD. Applied Surface Science. 2003; 216: 413–8.

[4] Avedillo MJ, Quintana JM, Roldán HP. Increased Logic Functionality of Clocked Series-Connected RTDS. IEEE Trans Nanotechnol. 2006; 5 (5): 606-11.

[5] Cheng YT, Ho JJ, Lee WJ, Tsai SY, Lu YA, Liou JJ, Chang SH, et al. Investigation of Low-Cost Surface Processing Techniques for Large-Size Multicrystalline Silicon Solar Cells. International J of Photoenergy. 2010; (2010): 1-6.

[6] Liu HC, Coon DD. Heterojunction double-barrier diodes for logic applications. Appl Phys Lett. 1987; 50 (18): 1246-8.
[7] Diamond SK, Özbay E, Rodwell MJW, Bloom DM, Pao YC, Harris JS. Resonant tunneling diodes for switching applications. Appl Phys Lett. 1989; 54 (2): 153-5.

Figure captions:

Fig. 1: J–V characteristics as measured at room temperature for the RTD structure with three different thicknesses of silicon dioxide. The inset shows the RTD structure and energy band diagram.

Fig. 2: The two-barrier structure for the series RTD of the P–V curves at room temperature. The left inset is the oscilloscope measurement results. The right inset is the circuit model.

Fig.3: Environmental temperature and relative humidity test of the RTD device stabilizer.

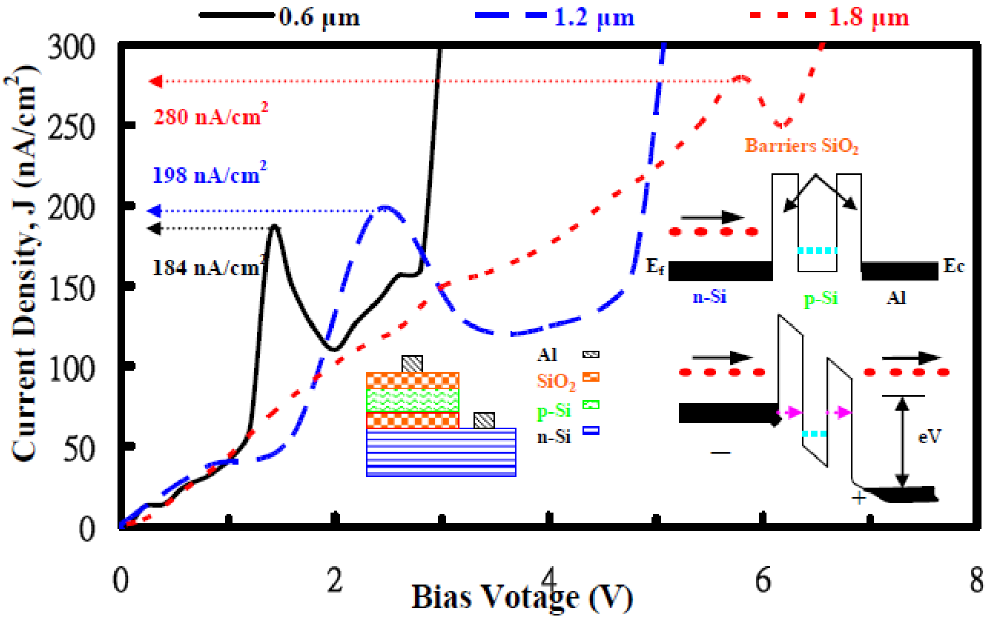

Figure 1

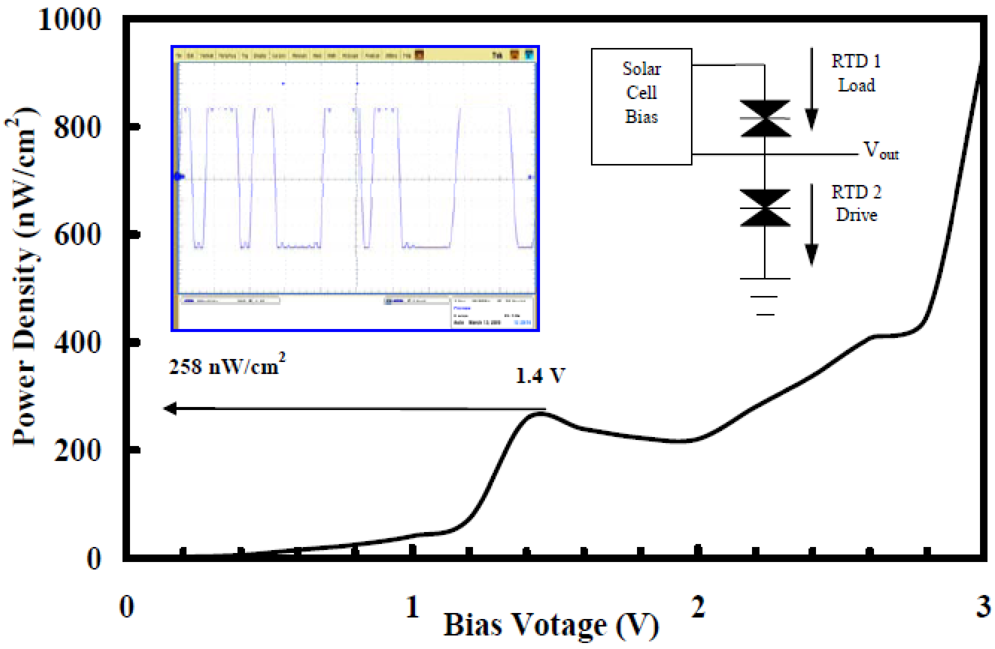

Figure 2

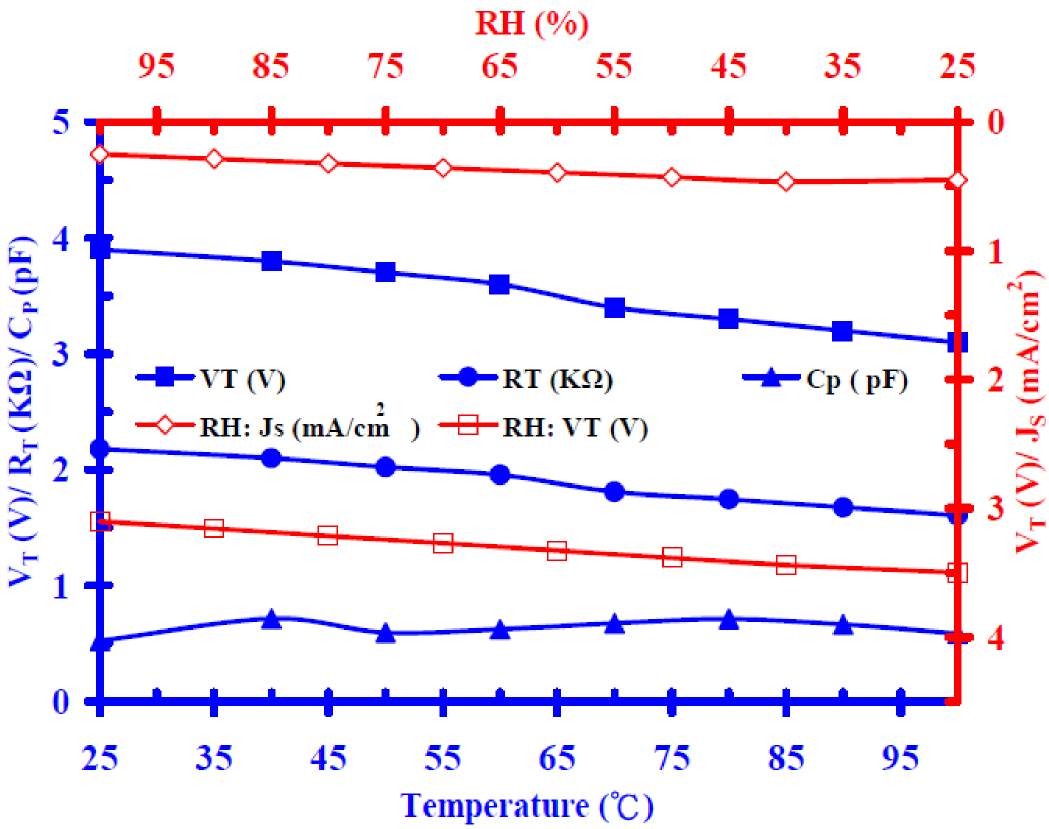
RH (%)
95 85 75 65 55 45 35 25
0 1 2 3 4
5 4 3 2 1 0
V_T (V)/ R_T (KΩ)/ C_P (pF)
V_T (V)/ J_S (mA/cm^2)
VT (V)
RT (KΩ)
Cp (pF)
RH: Js (mA/cm^2)
RH: VT (V)
25 35 45 55 65 75 85 95
Temperature (℃)

Figure 3